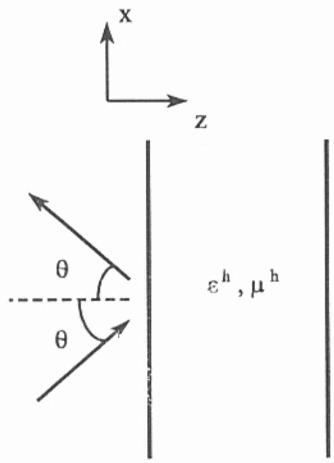

Figure 8. Equivalent anisotropic layer.

and for the parallel polarization:

$$E(x) = E_x(z) \qquad H(z) = H_y(z) \tag{17}$$

$$\begin{aligned} \epsilon_{eff} &= \epsilon_x \\ \mu_{eff} &= \mu_y - \tfrac{\mu_o \epsilon_o \sin^2\theta}{\epsilon_z} \ . \end{aligned} \tag{18}$$

With these expressions for the angular dependence on the effective material properties, we can now calculate reflection and transmission coefficients for composite structures.

4. REFLECTION FROM A CINDER BLOCK WALL

In this section, results for a one-dimensional periodic structure resembling a cinder block wall will be given (see Figures 1 and 4). Four block walls are analyzed: two different 14.5-cm (5.71-in) walls, one 7.2-cm (2.83-in) wall, and one 19.6-cm (7.72-in) wall. The dimensions of these different walls are shown in Table 1.

The 14.5-cm (5.71-in) block wall labelled block # 1 in Table 1 is represented as the layered structure shown in Figure 4, and has the following geometry: layers 1 and 5 are free space;

Table 1. Geometries of the concrete blocks

	Block # 1 [14.5-cm wall]	Block # 2 [14.5-cm wall]	Block # 3 [7.2-cm wall]	Block # 4 [19.6-cm wall]
l_2	2.25 cm	2.25 cm	1.7 cm	3.4 cm
l_3	10.0 cm	10.0 cm	3.8 cm	12.8 cm
a	2.6 cm	2.6 cm	2.8 cm	2.7 cm
d	14.3 cm	14.3 cm	9.5 cm	15.3 cm
ϵ_r	3.0	6.0	3.0	3.0
σ	$1.95 \cdot 10^{-3}$	$1.95 \cdot 10^{-3}$	$1.95 \cdot 10^{-3}$	$1.95 \cdot 10^{-3}$

layers 2 and 4 are a solid medium with $l_2 = 2.25\ cm$, $\mu = \mu_o$, $\epsilon_r = 3$ and $\sigma = 1.95 \cdot 10^{-3}$; and layer 3 is a medium with effective material properties given by equations (8) and (9) where $a = 2.6\ cm$, $d = 14.3\ cm$, $l_3 = 10.0\ cm$, $\epsilon_a = 3$ and $\sigma = 1.95 \cdot 10^{-3}$. Once the material properties of these layers are determined, the reflection coefficient can be obtained by using either classical layered media methods or classical transmission line methods. Figure 9 shows results for the reflectivity (defined as the magnitude squared of the reflection coefficient) of a block wall oriented both along the y-axis and x-axis (see Figure 1) for a perpendicularly polarized E field with a frequency of 900 MHz. Figure 10 shows results for a parallel polarization of the E field. These results were obtained using equations (16) and (18). Also shown in these figures are results for a solid layer of concrete ($\epsilon_r = 3$ and $\sigma = 1.95 \cdot 10^{-3}$) 14.5-cm thick.

From these figures it is apparent that the resonant behavior of the reflectivity cannot be achieved if a composite wall (block wall) is approximated by a solid layer. Correctly representing this resonant behavior is important for short path propagation. For large path propagation the reflection coefficient needed will correspond to angles approaching grazing (90°), and from Figures 9 and 10 show that the reflection coefficient for the composite wall and the solid wall approach one another. This point is further illustrated in the following example.

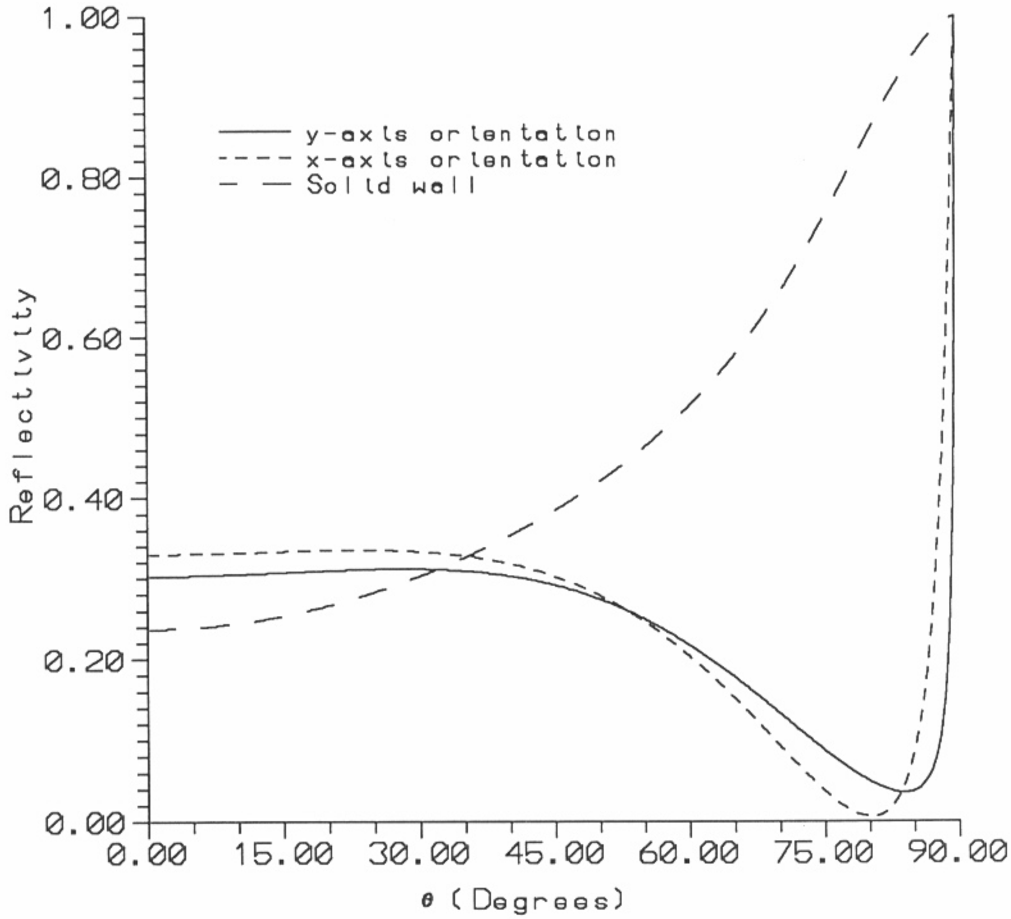

Figure 9. Reflectivity versus angle of incidence for a perpendicular polarized wave. These results are for block # 1 (see Table 1) with slabs oriented along both the $y-axis$ and $x-axis$ and with $f = 900$ MHz. The large dashed curve represents the results for a single layered slab of thickness equal to $2l_2 + l_3$, the solid curve represents the actual concrete block wall with the slabs oriented along the $y-axis$, and the small dashed curve represents the results for the actual concrete block wall with the slabs oriented along the $x-axis$.

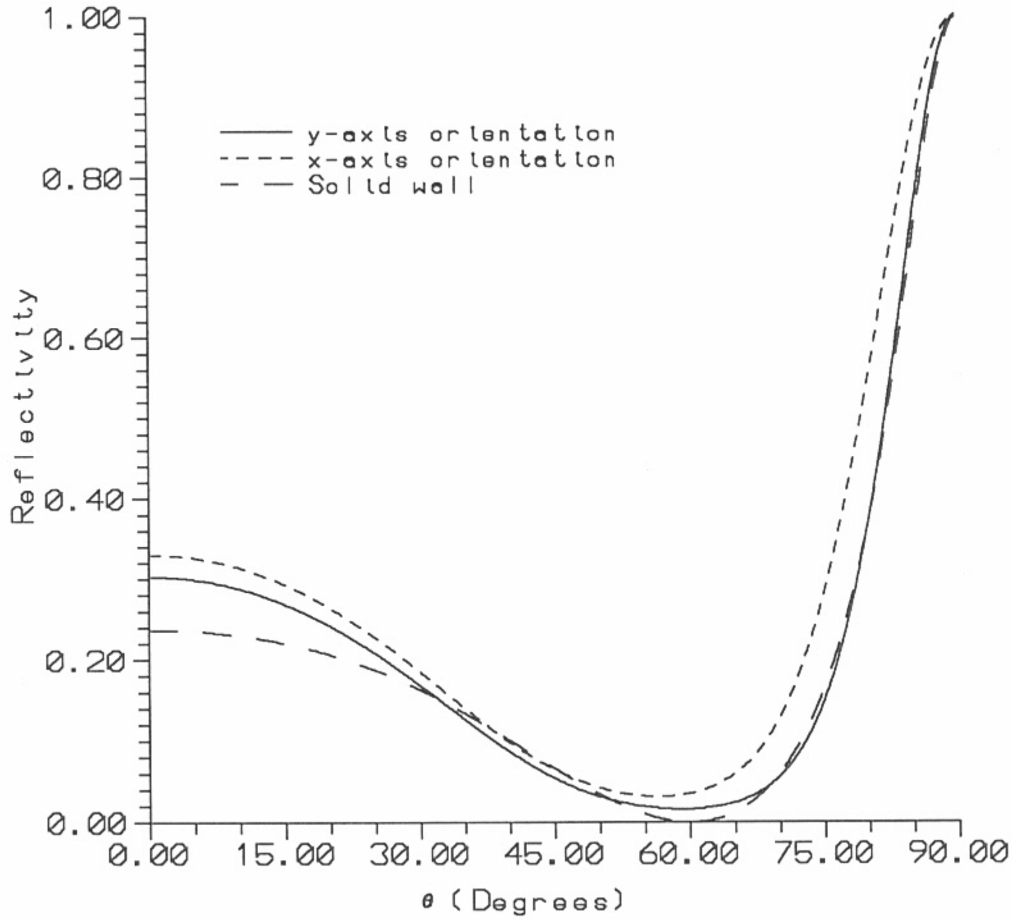

Figure 10. Reflectivity versus angle of incidence for a parallel polarized wave. These results are for block # 1 (see Table 1) with slabs oriented along both the $y - axis$ and $x - axis$ and with $f = 900$ MHz. The large dashed curve represents the results for a single layer slab of thickness equal to $2l_2 + l_3$, the solid curve represents the actual concrete block wall with the slabs oriented along the $y - axis$, and the small dashed curve represents the results for the actual concrete block wall with the slabs oriented along the $x - axis$.

Assume that a transmitting and receiving antenna are located 1 m from a wall. The power received (P_w) due to the wall reflection only, is given by:

$$P_w = 20 \log_{10} \left[\left| \frac{\Gamma}{x} e^{j(k\,x - \phi_\Gamma)} \right| \right] + P_o \quad [dB] \tag{19}$$

where P_o (in dB) is the transmitted power, k is the wavenumber; Γ and ϕ_Γ are the magnitude and phase of the reflection coefficient from the wall, respectively; and x is the total distance that the wave travels and is given by:

$$x = 2 \sqrt{w^2 + \left(\frac{d}{2}\right)^2} \tag{20}$$

where w is the distance between the wall and the transmitting and receiving antenna and d is the distance between the two antennas.

Figure 11 shows results for the received power as a function of antenna separation for a frequency of 900 MHz and for both antennas placed 1 m from the wall. The four plots in this figure correspond to a solid wall, a block wall oriented along the y-axis, a block wall oriented along the x-axis, and a perfect conductor. All these results were calculated assuming a perpendicularly polarized wave. These results indicate that for a long path length ($d > 500$ m) there is little difference between a solid wall, a composite wall, or a perfectly conducting wall. However, for short path lengths the power received by the solid wall or a perfectly conducting wall cannot reproduce the resonance behavior that is present in the composite walls. This figure illustrates that for short propagation paths, 10- to 20-dB inaccuracies can occur if one assumes the composite wall is treated as a solid wall.

As one might expect, the further the distance between the wall and the two antennas, the larger the separation distance between the antennas must be before the three curves coincide. Figure 12 illustrates results of the received power versus distance for a frequency of 900 MHz and for both antennas placed 4 m from the wall. For this example, the four curves correlate for $d > 1$ km.

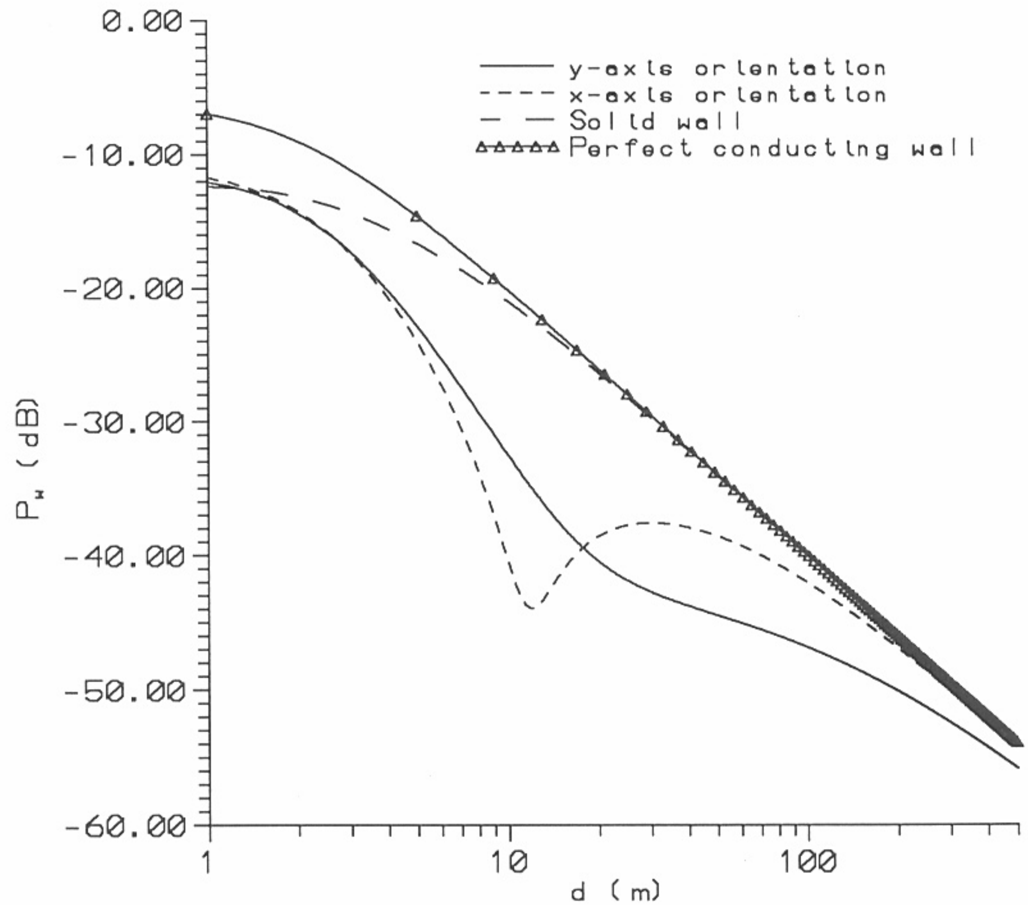

Figure 11. Reflected power off the wall versus antenna separation. These results are for block # 1 (see Table 1) with slabs oriented along the $y-axis$ and $f = 900$ MHz. The antennas are 1 m away from the wall.

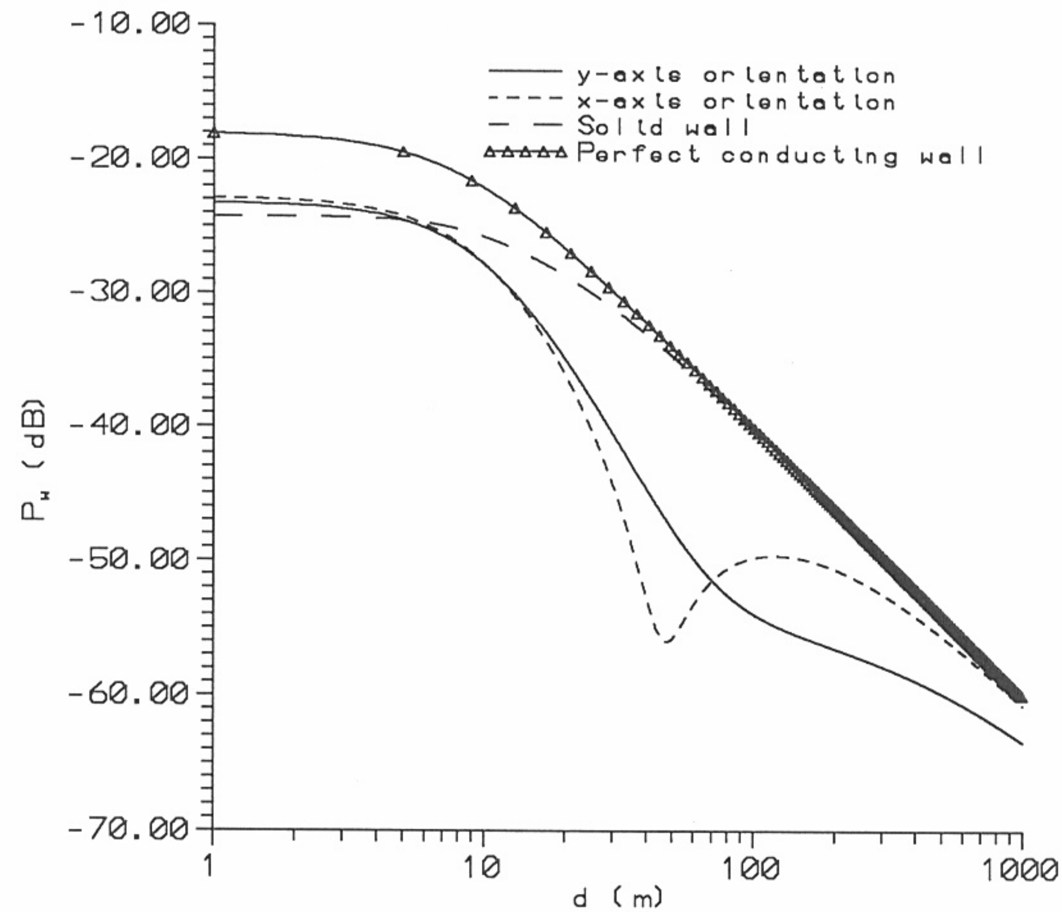

Figure 12. Reflected power off the wall versus antenna separation. These results are for block # 1 (see Table 1) with slabs oriented along the $y-axis$ and $f = 900$ MHz. The antennas are 4 m away from the wall.

In Figure 13 we show results for the total received power as a function of antenna spacing for an antenna placed above a perfectly conducting ground and between two walls. The results in Figure 13 are for a transmitter and receiver antenna spaced 1 m off of the ground and 1 m out from each wall. These two walls are assumed to be either a perfectly conducting wall, a single layer slab wall, or a concrete block wall. The received power is calculated by assuming that the total power is comprised of four different rays (Figure 3): the direct path, the ground reflection, and one reflection off each of the two walls. The predicted signal level is given by the following:

$$P_T = 20\ \log_{10}\left[\left|\frac{e^{j\,k\,d}}{d} + \Gamma_G \frac{e^{j\,k\,s}}{s} + 2\ \Gamma_w\ \frac{e^{j(k\,r - \phi_w)}}{r}\right|\right] + P_o \quad [dB] \tag{21}$$

where Γ_G is the reflection coefficient of the ground and for horizontal polarization $\Gamma_G = -1$ and for vertical polarization $\Gamma_G = 1$, Γ_w and ϕ_w are the magnitude and phase of the reflection coefficient of the walls; s (the reflection path off the ground) and r (the reflection path off the walls) are given by:

$$s = 2\sqrt{h^2 + \tfrac{d^2}{4}} \quad \text{and} \quad r = 2\sqrt{w^2 + \tfrac{d^2}{4}} \tag{22}$$

where h is the distance the antennas are above the ground, w is the distance the antennas are from the walls, and d is the separation of the two antennas.

The results are consistent with those shown in Figure 11. For small distance ($d < 1$ km) the results for the composite wall show a difference in received signal of 8 to 10 dB from the results for the other two types of walls. Figure 14 shows results for a transmitter and receiver antenna spaced 4 m away from each wall. This figure shows that between 40 and 500 m, the results for the block wall indicate an average of about 8- to 10-dB difference in received signal than that obtained from the solid or perfectly conducting wall. The nulls for the block wall are not as deep as those for the other two walls.

Depending upon frequency, the bulk material properties of the blocks, or the dimensions of the blocks, the composite wall may or may not behave like either a single slab wall or a

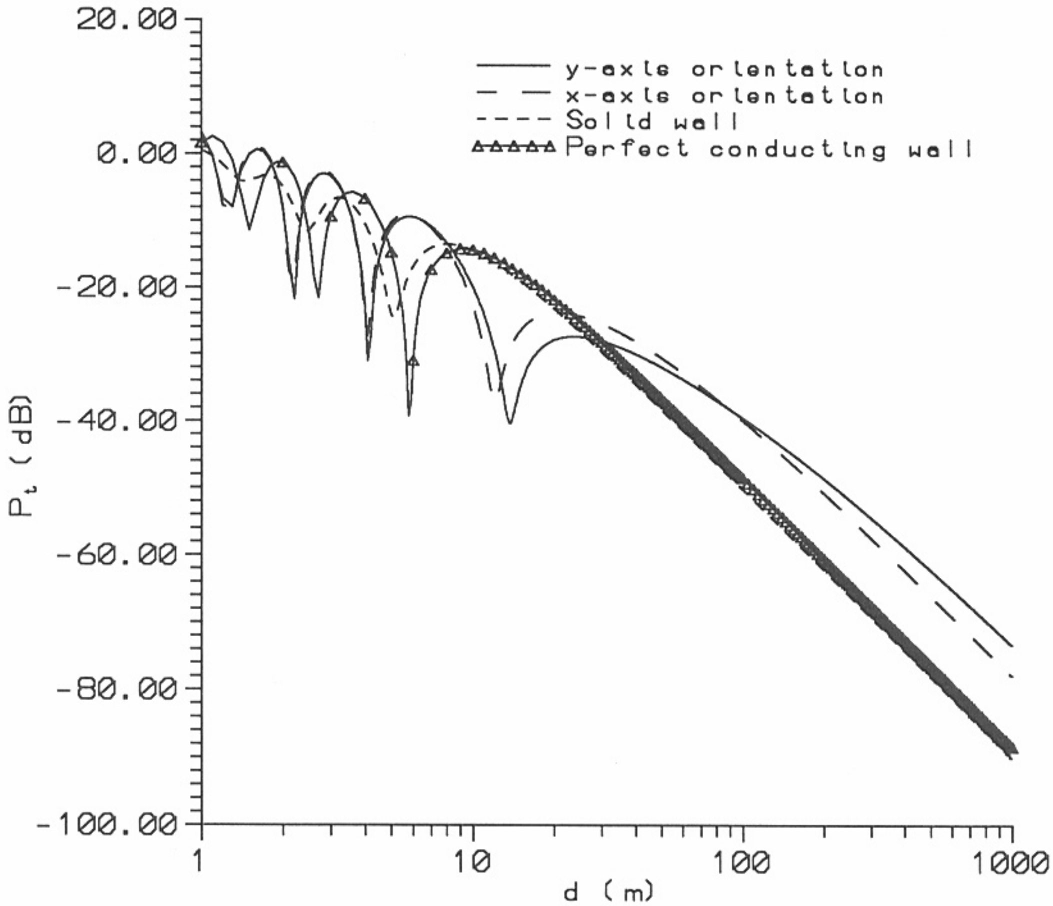

Figure 13. Received power versus antenna separation for the four-ray model. These results are for block # 1 (see Table 1) with slabs oriented along the $y-axis$ and $f = 900$ MHz. The antennas are 1 m off the ground and are spaced 1 m from each of the two walls.

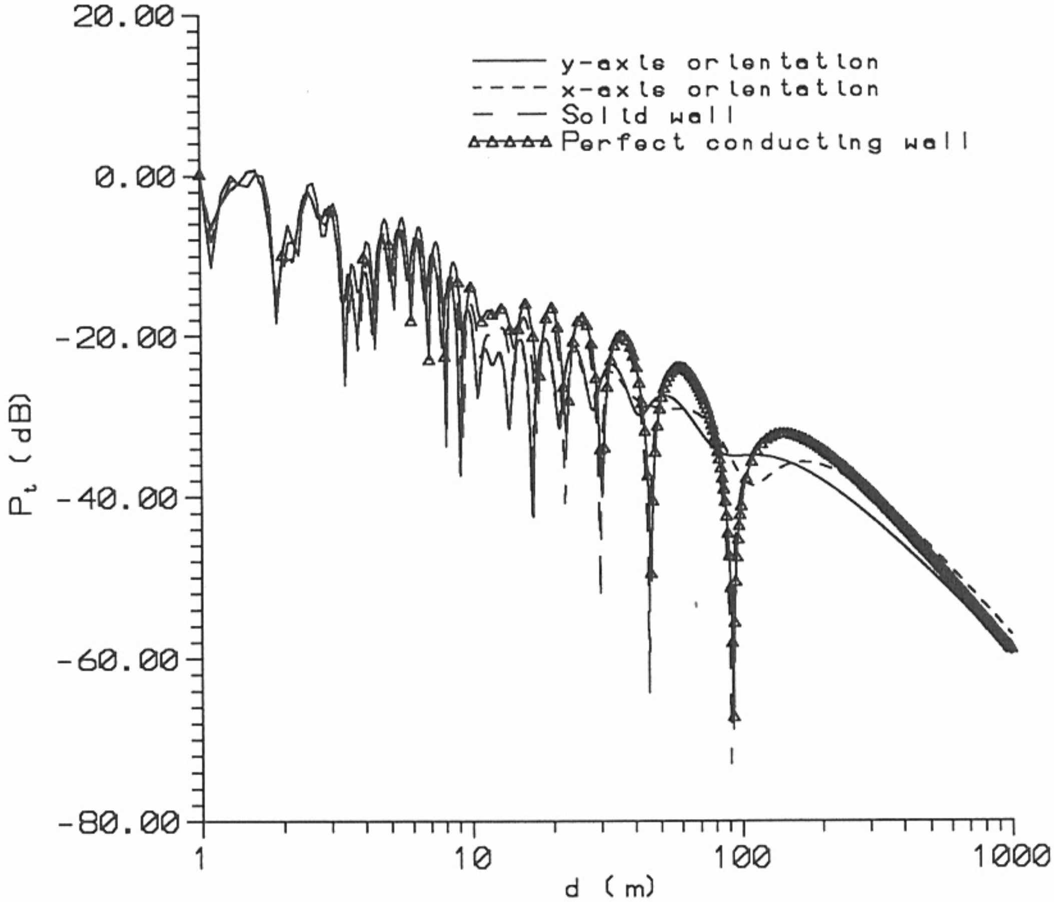

Figure 14. Received power versus antenna separation for the four-ray model. These results are for block # 1 (see Table 1) with slabs oriented along the $y-axis$ and $f = 900$ MHz. The antennas are 1 m off the ground and are spaced 4 m from each of the two walls.

perfectly conducting wall. Figures 15 and 16 show the results of the reflectivity for a wall composed of block # 2 (see Table 1). This block is identical to block # 1 with the exception that the dielectric constant (ϵ_r) is different. Figure 15 shows that for the perpendicular polarization (E-polarization), the block wall has very large values for the reflectivity for small incident angles, whereas the results for the solid slab have small values for the reflectivity for these small angles. For the perpendicular polarization, we should expect that if the total power received from the four-ray model (equation (21)) was calculated, then the results for the block wall would correlate fairly well with the perfectly conducting walls.

Figure 16 shows that for the parallel polarization (H-polarization) the reflectivity for block # 2 exhibits deep nulls, and further more, the results for the y-axis orientation composite wall corresponds very closely for large incident angles to the results for the solid wall. Therefore, the total predicted power from the composite wall is expected to correlate more closely to the solid wall than to the perfectly conducting wall. This is the case, and the results for the total received power for the four-ray model are shown in Figure 17. For an antenna separation between 5 and 60 meters, the signal predicted for a block wall is about 5 dB to 10 dB less than for a perfectly conducting wall.

Figures 18 and 19 show the reflectivity for a 7.2-cm (4-in) and 19.6-cm (8-in) block wall, respectively. The 7.2-cm (4-in) block wall corresponds to block # 3 in Table 1, and the 19.6-cm (8-in) block wall corresponds to block # 4 in Table 1. The results shown in these figures are for a perpendicular polarized wave. Results for the predicted signal levels of the four-ray model for these two block walls are shown in Figure 20 and 21.

The results in Figure 18 indicate that the reflectively of the composite wall is very similar to the results for the solid wall. Figure 20 shows that for the 7.2-cm (4-in) block wall, the predicted signal level correlates more closely with the solid wall than to the perfectly conducting wall. However, from Figure 20 it is shown that the total received power for the

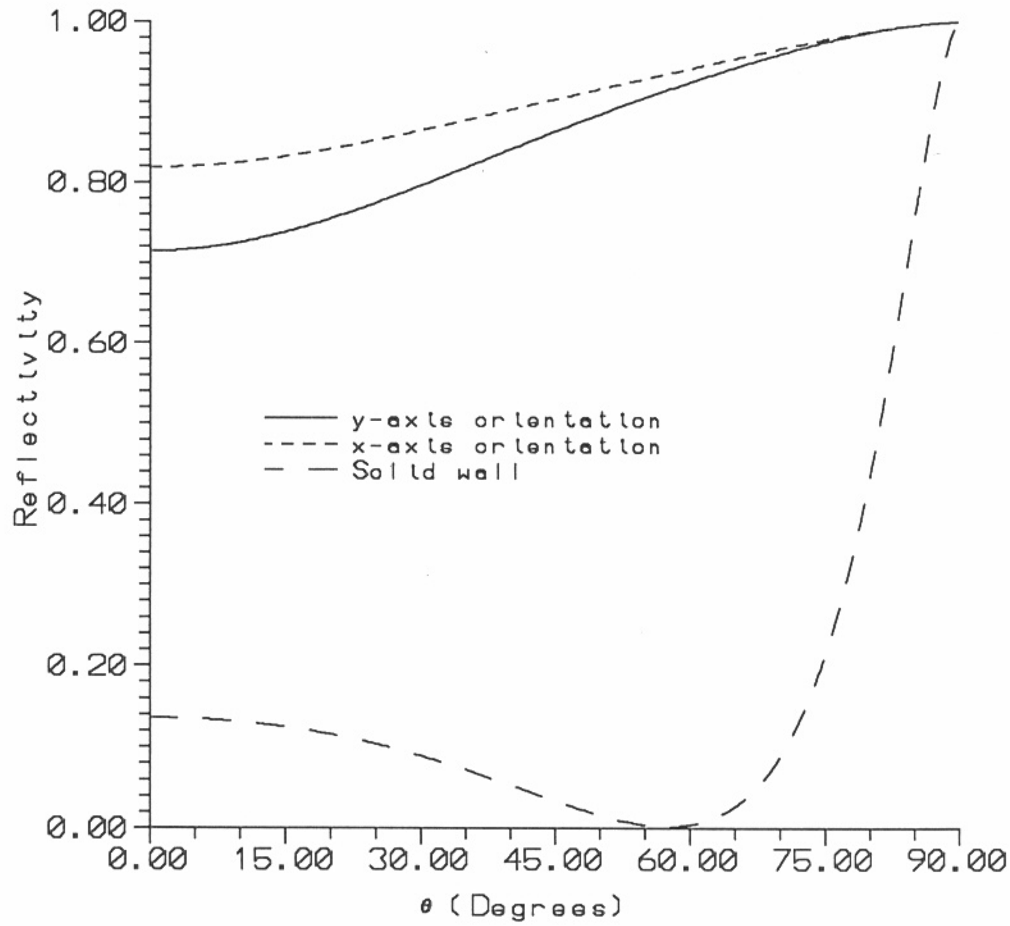

Figure 15. Reflectivity versus angle of incidence for a perpendicular polarized wave. These results are for block # 2 (see Table 1) with slabs oriented along both the $y-axis$ and $x-axis$ and with $f = 900$ MHz. The large dashed curve represent the results for a single layered slab of thickness equal to $2l_2 + l_3$, the solid curve represents the actual concrete block wall with the slabs oriented along the $y - axis$, and the small dashed curve represents the results for the actual concrete block wall with the slabs oriented along the $x - axis$.

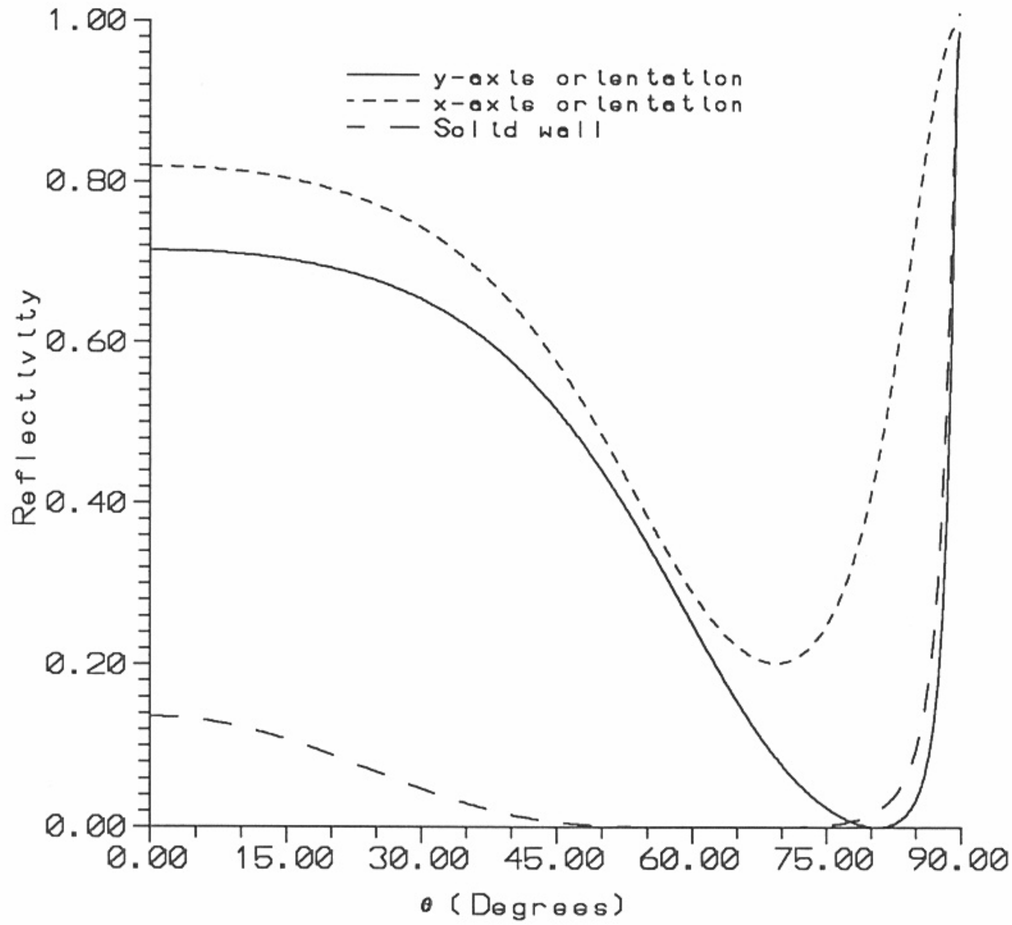

Figure 16. Reflectivity versus angle of incidence for a parallel polarized wave. These results are for block # 2 (see Table 1) with slabs oriented along both the $y-axis$ and $x-axis$ and with $f = 900$ MHz. The large dashed curve represent the results for a single layered slab of thickness equal to $2l_2 + l_3$, the solid curve represents the actual concrete block wall with the slabs oriented along the $y-axis$, and the small dashed curve represents the results for the actual concrete block wall with the slabs oriented along the $x-axis$.

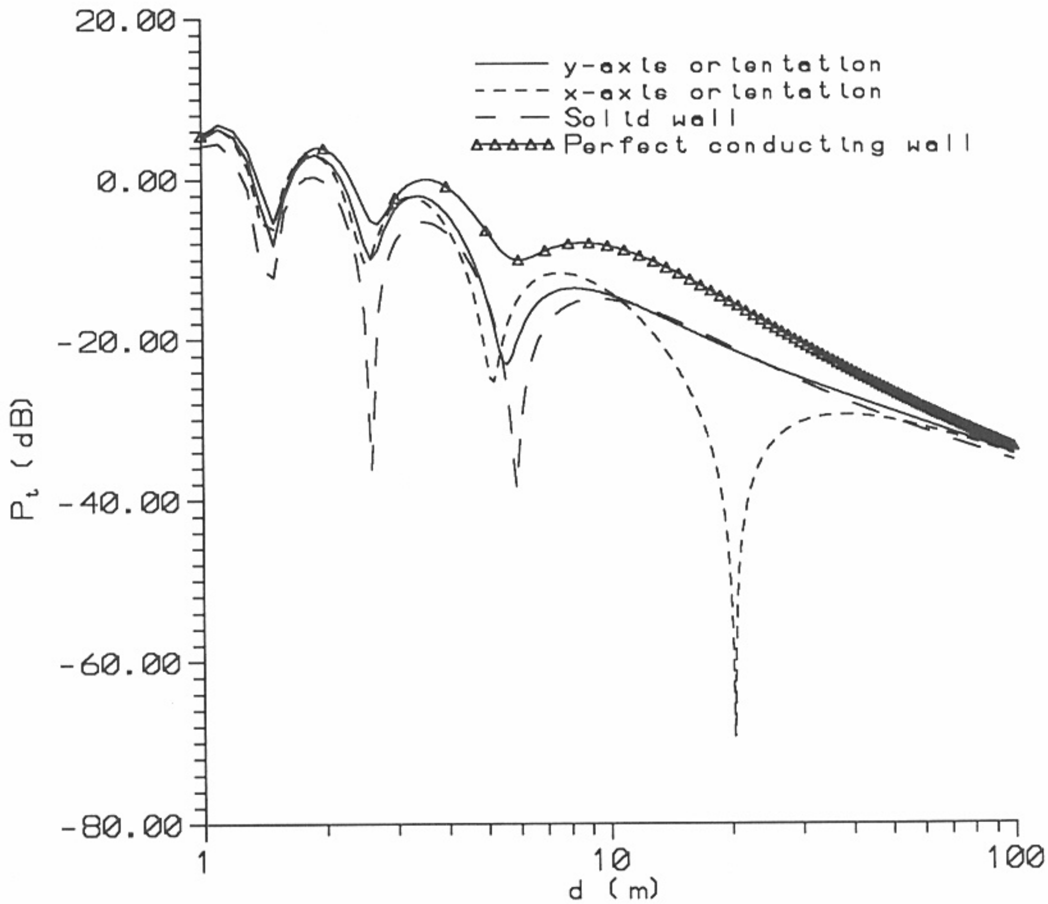

Figure 17. Received power versus antenna separation for the four-ray model. These results are for the parallel polarization for block # 2 (see Table 1) with slabs oriented along the $y-axis$ and $f = 900$ MHz. The antennas are 1 m off the ground and are spaced 1 m from each of the two walls.

solid and composite wall are not as close as might be expected upon examining the results in Figure 18, especially between 2 and 20 m. The total received power is a function of both the magnitude and phase of the reflection coefficient (Γ). The results in Figure 18 only depict the magnitude of Γ, the phase of Γ for the composite and solid walls can behave quit differently from each other depending upon the geometry and material properties of the walls, and this characteristic is equally important in determining the total received power.

These examples illustrate how the predicted signal level can vary for block walls with different geometries and material properties. Depending on the block wall parameters, the predicted signal level for short path propagation can correlate to either a solid slab wall, or to a wall composed of a perfect conductor. It can also behave differently from either of these two types of walls.

5. REFLECTION FROM A TWO-DIMENSIONAL BLOCK WALL

The two-dimensional composite structure shown in Figure 2 is replaced by the four-layer medium shown in Figure 5. Layers 1 and 4 are free space, layer 3 is a solid medium with $\epsilon_r = 6.1$, $\sigma = 1.95 \cdot 10^{-3}$ and $l_3 = 4.75\ cm$, and layer 2 is a periodic medium with effective material properties given by equations (8) and (9). For this medium it is assumed that $\epsilon_r = 6.1$, $\sigma = 1.95 \cdot 10^{-3}$, $a = 2.7\ cm$, $d = 15.3\ cm$ and $l_2 = 12.8\ cm$

Figure 22 shows results for the reflectivity of this composite structure for both perpendicular and parallel polarizations. Also shown in this figure are the results of a solid wall 17.55-cm thick, where $\epsilon_r = 6.1$ and $\sigma = 1.95 \cdot 10^{-3}$. Notice that the resonance behavior of the solid wall for the perpendicular polarization is different than that for the composite structure.